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A STUDY ON THE HYDROGEN-OXYGEN DIFFUSION FLAME IN HIGH SPEED FLOW

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A new type of apparatus was adapted to the study on the diffusion flame in high speed flow with the use of a shock tube /detonation tube combination. The flows behind the incident shock wave propagating into O₂-Ar mixture and the burned gas behind the detonation wave traveling into a fuel-rich H₂-O₂-Ar mixture were used to produce a fuel flow and an oxidizer flow respectively. The burned gas was issued through a nozzle in parallel to the oxidizer flow and two-dimensional flow field was established at the test section of the shock tube. The process from the starting of the flows to the formation of a diffusion flame was investigated by the pressure measurements in both tubes and by schlieren and interferometric photography. Also the ignition distances of the diffusion flames in quasi-steady state were measured from direct photography. As a result, a detonation tube was shown to be a useful device for producing a high speed and high temperature flow and it was confirmed that the ignition distance is greatly influenced by both velocity difference and hydrogen concentration.

INTRODUCTION

With the requirement for the increasingly faster flight of airplanes, the development of supersonic combustion technology has become one of important subjects in combustion engineering. Various methods of flame holding such as bluff-body, recessed wall, piloted flame and so on have been devised and developed to stabilize a flame in high speed flow. Those methods are used to hold a flame mainly in a premixed gas flow and are not necessarily adequate for the application to supersonic combustion. Recently the supersonic combustion techniques by a diffusion flame have received attention. The flow fields in these combustion systems are considerably complex due to the existence of a shock pattern and a turbulent mixing process. While numerous studies (1)~(5) have been conducted in this field, they have not given enough information to design a combustor of a scramjet engine. On executing an experiment of such supersonic combustion using a steady flow, a huge experimental facility is needed because a large amount of high temperature air flow must be supplied. Moreover, it may be difficult to vary the experimental conditions over a wide range employing a steady flow apparatus.

The detonation tube, as well as the shock tube, is considered to be a simple and convenient device to produce a high temperature gas flow. Behind a

steadily propagating detonation wave, a uniform gas flow of high temperature is formed and also its physical conditions can be evaluated from the characteristic values at Chapman-Jouguet point. Moreover, the use of a detonation tube has the additional advantage that the starting time of a flow can be regulated easily with an electric circuit by firing the detonable mixture in the detonation tube.

In this work, a new type of apparatus was designed for the study on the diffusion flame with the use of a shock tube/detonation tube combination. The detonation tube served as a generator of a fuel flow of high temperature and the shock tube acted as a short duration wind-tunnel of an oxidizer flow. This paper reports the structure of the apparatus and the flow characteristics in both tubes and presents the preliminary results obtained by optically observing the diffusion flame.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus employed in this study consisted of a shock tube and a detonation tube, which were arranged in parallel to each other and connected with a bent-tapered nozzle at the test section of the shock tube as shown in Fig.1. The shock tube served as a short duration wind-tunnel and the incident shock wave propagating into O₂(20%)-Ar(80%) mixture generated an oxidizer flow. The shock tube was a conventional one with a 70mm i.d., 3m-long driver section and a 43 mm square, 6 m long driven section. A test section with two glass windows was installed at the downstream end of the driven section and was connected to a dump-tank across a plate valve. A needle in the driver section, which was driven by a solenoid, was used to synchronize the rupture of the diaphragm(1) with the photographing by a high speed camera. On the other hand, the detonation tube produced a fuel flow. The burned gas behind a detonation wave propagating into a fuel-rich H₂-O₂-Ar mixture was issued through the nozzle in parallel to the oxidizer flow in the shock tube. The detonation tube was a circular pipe with 32.9 mm i.d. and 1.75 m length. One end of the detonation tube was closed and the other end was connected to the nozzle across the diaphragm(2).

An igniting plug was equipped on the detonation tube near the diaphragm(2) and a circular pipe with numerous holes was inserted into the detonation tube to accelerate the transition from a deflagration wave to a detonation wave.

Two pressure transducers were equipped on the test section and at the location of 2.05 m upstream from its center. The former signal was employed to monitor the pressure change in the test section and the latter signal acted as the signal source for triggering the spark ignitor. The timing of the firing is regulated using a delay circuit so that both the oxidizer flow and the fuel flow may start at almost the same time. Also, both the signals were utilized for the measurement of shock wave velocity which determines the flow conditions of the oxidizer flow. Another pressure transducer was equipped at the closed end of the detonation tube, which enabled us to ascertain whether the complete transition to a detonation wave was established.

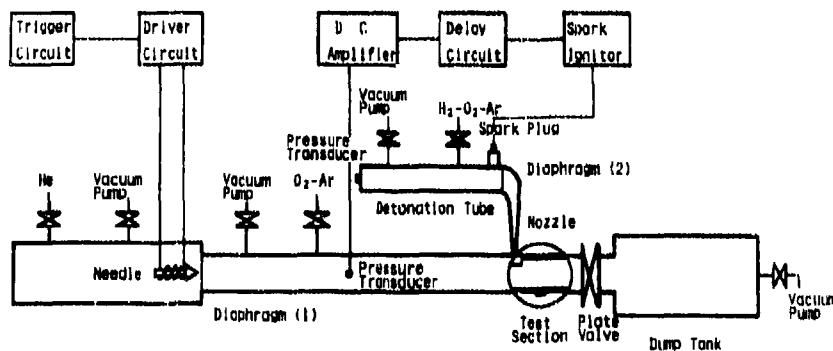


Fig. 1. Experimental apparatus

The test section is shown in Fig. 2. The nozzle, which was curved downward from the joint with the detonation tube, was introduced into the shock tube along the upper wall of the test section. The cross section of the nozzle was contracted to a 43 mm x 2 mm rectangle at its exit and a two-dimensional parallel flow field was formed in the test section.

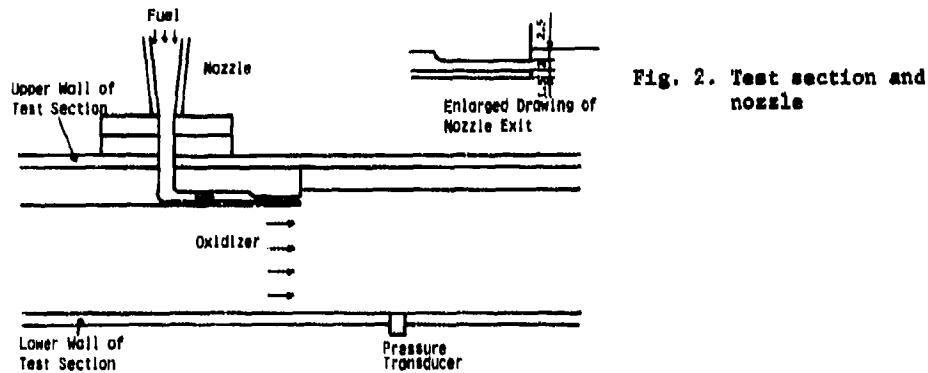


Fig. 2. Test section and nozzle

Each run was shot in the following way. After the driver and driven section of the shock tube, the detonation tube, and the dump-tank were evacuated, pressurized helium, the oxidizer mixture, the fuel mixture and air were introduced into these tubes to the desired pressure respectively. The pressure in the dump-tank was kept at the same level with that in the driven section, and the plate valve is opened. The diaphragm(1) was ruptured by the needle when the framing speed of the high speed camera has reached to around 5000 pps and a shock wave propagated into the driven section. In the already mentioned way, the mixture in the detonation tube was fired with the igniting plug. As a result, the diaphragm(2) ruptures due to the pressure rise in the detonation tube and the burned gas behind the detonation wave issued into the test section through the nozzle in parallel to the oxidizer flow. Schlieren, interferometric and direct photography were employed to observe the flow field.

FLOW CONDITIONS

While the use of a detonation tube has some advantages in producing a high temperature flow, it should be noted that the fuel flow conditions can not be chosen arbitrarily. The strength of the mixture used to produce a fuel flow must be chosen so that the transition time to a detonation wave becomes short compared with the characteristic time, which is defined as the ratio of the detonation tube length to the velocity of the detonation wave. This imposes a severe restriction on the experimental conditions of the fuel flows. In addition, there is a correlation between the temperature and the velocity, and neither can be varied independently. Four kinds of the mixture ($H_2:O_2:Ar = 3:1:2$, $3:1:3$, $5:2:3$ and $4:1:2$) were used and their initial pressure was fixed at 700 Torr. Under these experimental conditions, it was confirmed from the pressure measurements that smooth transition to a detonation wave took place. The flowing conditions of fuel were evaluated based on the relationship of isentropic flow and the properties of the mixture at the Chapman-Jouguet point. Namely, the characteristic values at the Chapman-Jouguet point were determined from the composition and the pressure of the initial mixture, and flowing conditions of the downstream from the Chapman-Jouguet point were calculated under the conditions that the flow is isentropic and the sonic flow is established at the nozzle exit. On the other hand, the flowing conditions of oxidizer were determined from the measurement of the incident shock wave velocity in usual way.

The flowing conditions of the oxidizer and of the fuel at the nozzle exit are listed in Table 1. The temperature and Mach number of the oxidiser flow were varied over the range from 600 K to 1150 K and from 0.89 to 1.23 respec-

tively. The temperature and velocity of the fuel flow at the nozzle exit were in the narrow range from 2140 K to 2360 K and 1150 m/s to 1190 m/s respectively. The mole fraction of hydrogen could be changed in the relatively wide range from 0.15 to 0.31.

Table 1. Flow conditions of oxidizer and fuel

Run No.	Oxidizer Flow				Fuel Flow				Velocity Parameter*	Concen. Parameter**
	Press. MPa	Temp. K	Velocity m/s	Mach No.	Press. MPa	Temp. K	Velocity m/s	H ₂ %		
1	0.057	1150	770	1.23	0.31	2270	1130	19.6	0.19	2.32
2	0.062	1000	680	1.18	"	"	"	"	0.25	1.83
3	0.065	890	610	1.12	"	"	"	"	0.30	1.54
4	0.080	750	520	1.03	"	"	"	"	0.37	1.06
5	0.071	600	400	0.89	"	"	"	"	0.48	0.98
6	0.052	1070	720	1.20	0.29	2140	1050	16.4	0.19	2.66
7	0.061	990	670	1.17	"	"	"	"	0.22	2.12
8	0.062	850	590	1.10	"	"	"	"	0.28	1.80
9	0.078	740	510	1.01	"	"	"	"	0.35	1.58
10	0.071	600	400	0.89	"	"	"	"	0.45	1.86
11	0.057	940	650	1.15	0.31	2360	1150	15.4	0.28	1.68
12	0.062	1000	680	1.18	0.29	2180	1190	31.1	0.27	3.39

* Velocity parameter = $(U_f - U_o) / (U_f + U_o)$

** Concentration parameter = $(P_f \cdot X_{H_2} / M_f) / (P_o \cdot X_{H_2} / M_o)$

CHARACTERISTICS OF FUEL AND OXIDIZER FLOW

The flowing conditions listed in Table 1 are valid under the conditions that the flow in the nozzle is steady and the oxidizer flow is not influenced by the existence of the fuel flow. In order to investigate whether these conditions were satisfied, the pressure measurements were made at the test section and at the nozzle prior to the observation of diffusion flame. In Fig.3, the pressure change in the nozzle (upper trace) and in the test section (lower trace) are shown. The first rise on the both traces represents the issue of the burned gas into the nozzle and the test section. The pressure in the nozzle, then, gradually increases and reaches a certain level. The pressure at this time was 0.54 MPa, which coincided well with the evaluated value. It is considered that the steady flow has been established at this time. This steady state is broken by the propagation of the detonation wave, which has reflected at the closed end of the detonation tube, into the nozzle. The time required for the establishment of the steady state and the duration of the steady state are estimated to be 0.7 ms and 1.0 ms respectively. On the other hand, the pressure in the test section is kept constant for 0.8 ms after showing the temporary fluctuation due to the issue of the burned gas as well as the pressure in the nozzle. Then the gradual increase is observed and followed by the large jump due to the arrival of the reflected detonation wave.

Another pressure measurement in the test section made clearer the characteristics of the oxidizer flow. Three traces in Fig. 4 are the signals of the pressure transducers which were equipped on the test section at intervals of 200 mm. The symbols A, B, C and D indicate the commencement of the fuel flow, the incident shock wave, the compression wave and the reflected detonation wave

respectively. It was found from these traces that the steady flow of the oxidizer lasted for about 0.9 ms until it was interrupted by the compression wave which propagated upstream. Such a compression wave was observed even when Ar was used for the shock tube flow instead of O₂-Ar mixture. Therefore, it is considered that the compression wave does not result from the interaction of the fuel flow and the oxidizer flow, but from the characteristics of the shock tube flow. Although the period in which both of the flows were steady was short in this work, earlier start of the fuel flow will make the duration of the steady state longer.

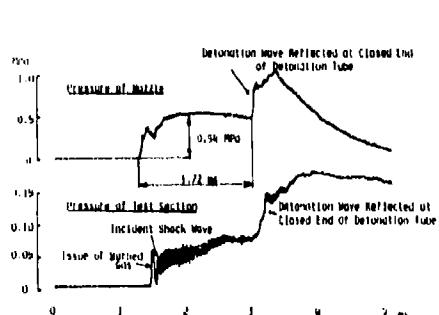


Fig. 3 Pressure changes in the test section and nozzle.

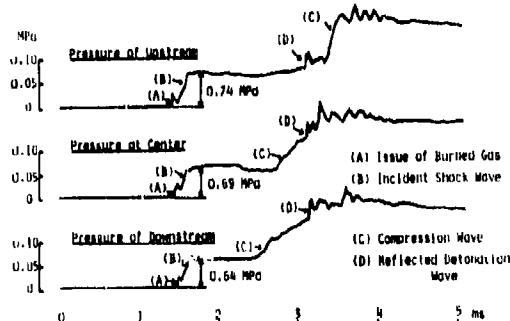


Fig. 4 Pressure changes in the test section.

OBSERVATION OF FLOW FIELD

Figs. 5 and 6 are typical schlieren and interferometric photographs taken to observe the flow field. The pressure change in the test section is also shown in Fig. 5. The figures under these photographs represent the elapsed time from the issue of the burned gas into the test section and the numbers on the pressure trace correspond to those of the photographs. These sequential photographs clarify the flow pattern and the formation process of the diffusion flame. In the first photograph of Fig. 5, the burned gas has been just issued and the mixing region has not been formed yet over the whole region of the test section. The photographs (1)-(3) show the process from the starting of the flows to the establishment of a steady flow. Two oblique shock waves originate from the upper and lower tip of the nozzle exit with the starting of the fuel flow. The former reflects at the upper wall of the test section and propagates across the fuel flow into the free stream of the oxidizer flow. The latter propagates directly into the free stream of the oxidizer. A rarefaction wave also originates from lower tip of the nozzle exit. After reflecting at the upper wall, the rarefaction wave interacts with the oblique shock wave reflected at the upper wall in the free stream of the oxidizer flow, which results in a single oblique shock wave in the oxidizer flow. The shock pattern shows little change in the photographs (3)-(4). This means that a steady flow has been established. After 1.05 ms, it is observed that the shock pattern is disturbed from the downstream by a compression wave. This compression wave corresponds to the one detected by the pressure measurement in the test section.

Fig. 6 is the interferometric photograph of the flow field in a steady state. From the narrow spacing and the large shift of the fringes in the vicinity of the nozzle exit, the fuel flow is found to rapidly expand immediately after issued into the test section. On the contrary, the oblique shock waves bring about slight deceleration and temperature rise to the both flows. The fringes are almost vertical in the fuel and the oxidizer flow except the mixing region. Although the fringe shift of the mixing region is large in the neigh-

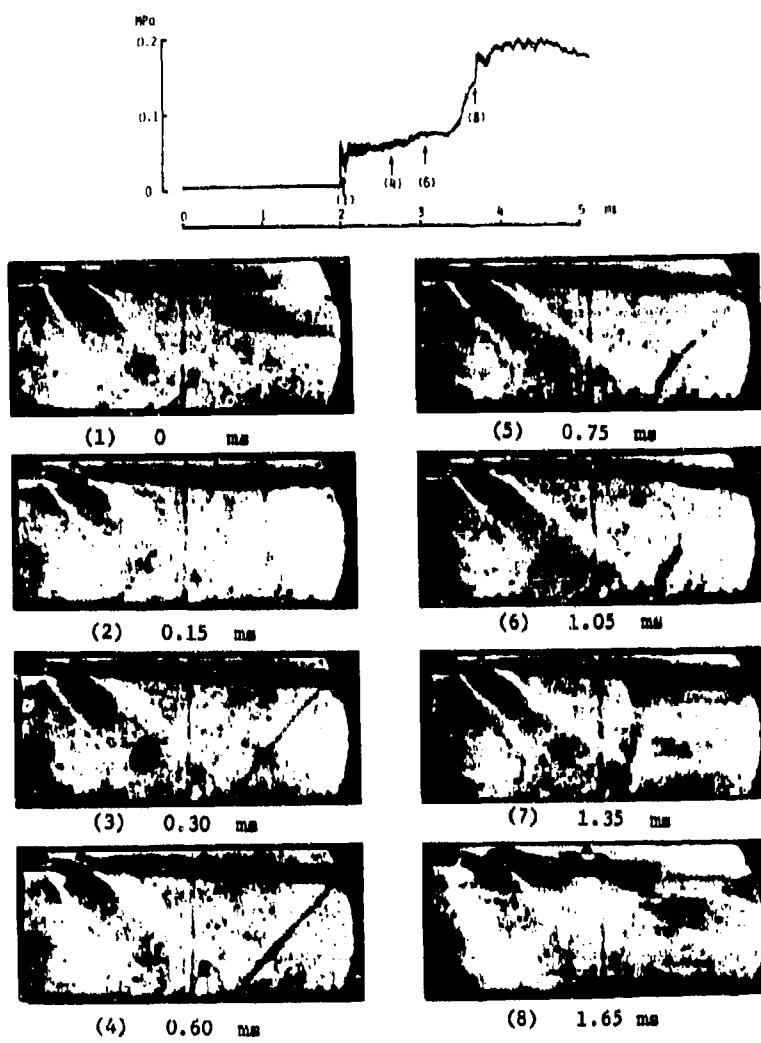


Fig. 5 Schlieren photographs showing typical flow pattern.

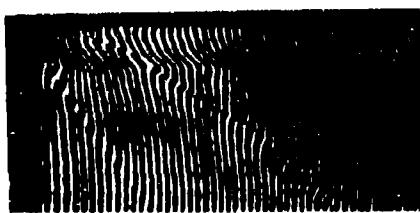


Fig. 6 Interferometric photograph showing the steady flow field.

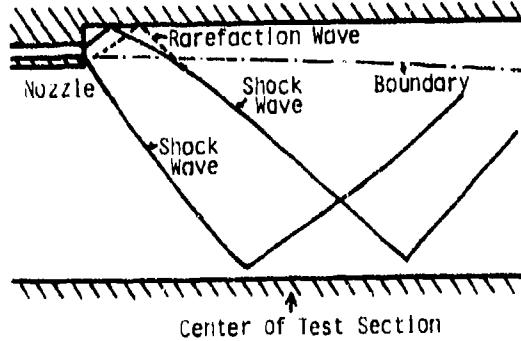


Fig. 7 Schematic drawing of flow field.

borhood of the nozzle exit, it gradually decreases as the mixing of the fuel flow and the oxidizer flow proceeds. These facts suggest that the flow conditions of the fuel change rapidly from those calculated due to the expansion in the test section. It may not be adequate to use the flowing conditions evaluated at the nozzle exit in discussing the properties of the diffusion flame. If the experimental conditions are chosen so that the pressure at the nozzle exit agrees with that of the oxidizer flow, it will be capable of producing the same flowing conditions with those calculated. Fig. 7 is a schematic drawing of the flow pattern which was synthesized from these observations.

OBSERVATION OF DIFFUSION FLAME

Fig. 8 is the direct photographs which show the formation process of a diffusion flame. The figures under the photographs indicate the elapsed time from the issue of the burned gas. Since the fuel is issued before the oxidizer flow starts, the early issued portion of the fuel almost reaches the opposite side of the test section as shown in the first photograph. In the second photograph, the whole mixing region is brightening. The emission, however, does not mean the formation of a diffusion flame because the fragment of the diaphragm burns with its exposure to the surrounding high temperature gas. As the fuel flow approaches its steady state, the ignition point moves downstream. It then stays at a distance apart from the nozzle for a short time and turns back upstream with the passage of the compression wave. In this way, a steady diffusion flame appears to exist, though its duration is short. Therefore, the effect of the velocity difference between the fuel and oxidizer flow and the hydrogen concentration on the ignition distance have been investigated based on the direct photographs of the steady diffusion flame.

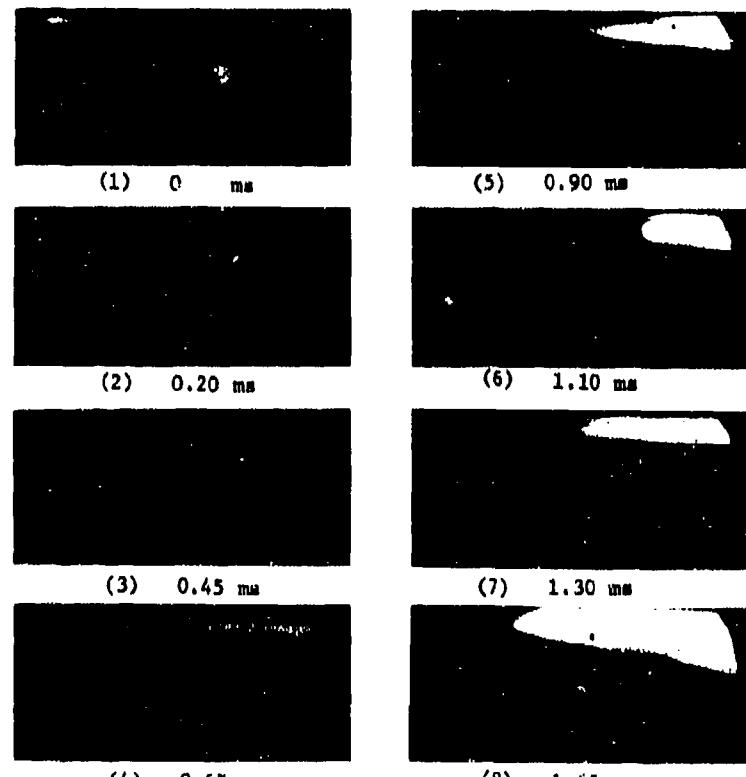


Fig. 8 Direct photographs showing the formation of a diffusion flame.

Each effect can be seen in Fig. 9. Velocity parameter ψ is defined as $(U_f - U_o) / (U_f + U_o)$ and stands for a measure of the magnitude of the velocity difference between the both flows. On the other hand, concentration parameter ϕ is defined as $(f_f' X_w/M_f) / (f_o' X_w/M_o)$ and represents the over-all mole ratio of hydrogen to oxygen. The change of the velocity parameter ψ was caused mainly by the oxidizer velocity, because the velocity of the fuel flow could not be varied over a wide range as described above. Fig. 9 shows a general trend that the ignition distances become shorter as the velocity difference increases. The temperature of the oxidizer flow decreases with the increase of ψ due to a correlation between the temperature and the velocity of the oxidizer flow. Therefore, it may be concluded that the velocity difference greatly influences the ignition distance of the diffusion flame. The effect of hydrogen concentration can be seen by comparing the experimental points of different hydrogen concentration. In the range of hydrogen fraction from 0.15 to 0.20 hydrogen concentration has little effect on the ignition distance. On the contrary, in the case of the higher hydrogen concentration (0.31), the outstanding increase of the ignition distance was found. These experimental results seem to suggest that the ignition distance increases rapidly when the concentration parameter exceeds 2.5.

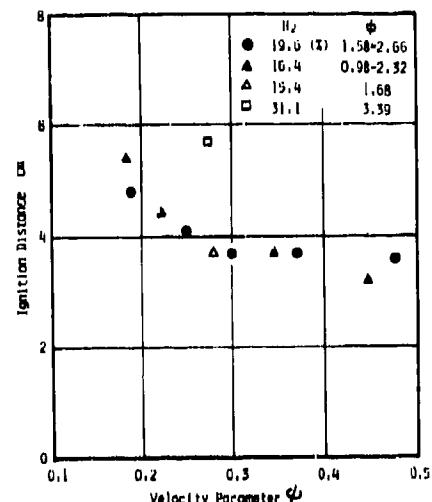


Fig. 9 The effect of velocity difference and hydrogen concentration on ignition distance.

CONCLUDING REMARKS

A shock tube/detonation tube combination has been adapted to the study of a diffusion flame in high speed flow. The process from the starting of the flows to the formation of a diffusion flame was investigated by the pressure measurements in both tubes and by schlieren and interferometric photography. Also the ignition distances in a steady state were measured by direct photography. As a result, a detonation tube was shown to be a useful device for producing a high speed and high temperature gas flow and it was confirmed that the ignition distance is greatly influenced by both velocity difference and hydrogen concentration. The pressure difference between the nozzle exit and the oxidizer flow resulted in a more complex flow field. This may be resolved by properly selecting the initial pressure in both tubes. The improvement of the apparatus or the proper choice of the experimental conditions would make possible more detailed investigation of the diffusion flame. Moreover, modification in the combination may offer new possibility to the application of a detonation tube to the study of high speed gasdynamics.

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